

Modelling V838 Monocerotis as a *Mergeburst* Object

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Abstract. We discuss the main observational facts on the eruption of V838 Monocerotis in terms of possible outburst mechanisms. We conclude that the stellar merger scenario is the only one, which can consistently explain the observations.

1. Introduction

The outburst of V838 Monocerotis was discovered at the beginning of January 2002 (Brown 2002). After about a month it suffered another outburst and reached a luminosity of $\sim 10^6 L_{\odot}$. Initially thought to be a nova, the object soon appeared unusual and enigmatic in its behavior. The eruption, as observed in the optical, lasted about three months. After developing an A-F supergiant spectrum at the optical maximum at the beginning of February 2002, the object showed a general tendency to evolve to lower effective temperatures. In April 2002 it almost disappeared from the optical but remained very bright in infrared, becoming one of the coolest M-type supergiants yet observed. A detailed discussion in Tylenda & Soker (2006) shows that novae (or novae-like) outburst models and born-again asymptotic giant branch (AGB) stars cannot account for basic properties of V838 Mon. The merger of two stars, on the main sequence or evolving toward the main sequence, emerged as the most promising model. Our view is that the observations and their analysis (although not completed) that were presented at the first meeting devoted to this object (held in La Palma May 2006), are all in support of the stellar binary merger model.

Stellar mergers have been recognized for a long time as events which can be important for evolution of binary systems. Also in discussions of globular clusters stellar mergers are usually considered as the most probable source of blue stragglers e.g. De Marco et al. (2005, and earlier references therein; Sills, Adams, & Davies 2005). However, the main interest in these cases has been directed towards understanding the nature of the final product of a merger in terms of its mass, chemical structure and farther evolution. Little attention has usually been paid to direct observational appearances of these events. As we think that the appearance itself of merger events will attract more attention in

the future, we would like to term these type of violent merger events that lead to V838 Mon type events, *mergebusts*.

In this paper written to the proceedings of the meeting, we summarize the main properties of V838 Mon that are relevant to its modelling, mainly as they were presented or cited during the meeting. We then summarize some of our results published elsewhere regarding the merger model. As we summarize the introduction to the final discussion of the meeting as presented by one of us (Soker), we mainly cite talks from the meeting as was done during the original presentation, assuming each paper will present the most updated results, and have a complete list of relevant references to its subject. We also hope that all of these papers will be posted on astro-ph, therefore be freely available.

2. Mass

Despite large amount of observational data, relatively little efforts have been done to deduce physical properties, in particular the envelope mass, mass loss, and mass of echoing material. We will try to estimate these from the few works that derived these quantities.

2.1. The Mass of the Surrounding Material

Despite several talks on the echo of V838 Mon (Liimets, Kolka, & Kipper 2006; Crause 2006; Santander-Garcia & Corradi 2006; Henden 2006; Bond 2006; Sparks 2006) no mass estimate was given, beside by Ashok's group. Ashok (Ashok et al. 2006) presented in his talk an estimate based on IR echo formed by dust emission. The estimated gas+dust mass from the IR echo is $M_{\text{echo}}(\text{IR}) \sim 150M_{\odot}$ (Banerjee et al. 2006). This estimate met some objection from a number of people e.g., because the IR echoing is concentrated in a small region at any given time (Sugerman 2006). However, it seems quite reasonable, and may fit other estimates.

V838 Mon stayed near its maximum luminosity for a time $\Delta t_o \simeq 2$ months. Let the echoing gas reside inside a radius $R_{ec} \sim 2$ pc. Simple estimates show that the echo comes from a volume fraction of $f_{ec} \sim (c\Delta t_o/R_{ec}) \sim 0.03$. However, the echoing material is not uniform, and it is possible that there was more dust in the echoing region than the average in the region, say by a factor of $f_u \sim 3$. It is possible that there are other IR sources in the field, which cause diffuse IR emission with low surface brightness, so the echo accounts for, say, $f_s \sim 0.5$ of the IR emission in the field. Indeed Afsar & Bond (2006) claimed for a young open cluster surrounding V838 Mon, which could heat this dust. Over all, the corrected IR mass in the volume is $M_{\text{echo}}(\text{corrected} - \text{IR}) \sim M_{\text{echo}}(\text{IR})[(f_s/(f_{ec}f_u))]$, which for the above values is $M_{\text{echo}}(\text{corrected} - \text{IR}) \sim 900M_{\odot}$.

Sparks (2006) presented some properties of the echo in the visible light. In a private conversation he estimated the gas particle number density in the echoing matter to be $n \sim 200 \text{ cm}^{-3}$. For an echoing region having radius R_{ec} (even though the echoing region at any time is not a sphere), and filling factor f_e the total mass from the echo in the visible is $M_{\text{echo}}(\text{visible}) \simeq 100(R_{ec}/2\text{pc})^3(f_e/0.5)M_{\odot}$. This value is lower than the above estimate based on the IR echo measurements of the Ashok's group.

The results from CO observations are more difficult to reconcile with the above estimates, and require photo-dissociation of CO molecules. Kaminski et al. (2006) gave a limit on the total molecular mass of $\sim 300M_{\odot}$ inside a radius of $r = 5\text{pc}$ around V838 Mon. This translates to a limit of $\sim 20 - 50M_{\odot}$ inside a radius of $r = 2\text{pc}$. Deguchi (2006) has CO observations of five regions, each of radius 7.5 arcsec, around V838 Mon. He reported the detection of emission in one region, with an estimated mass of $M_{\text{CO-spot}} \simeq 1M_{\odot}$. This translates to a total mass of $\sim (60/7.5)^2 M_{\text{CO-spot}}/4 \simeq 16M_{\odot}$ inside $r \simeq 60\text{ arcsec} \simeq 2\text{pc}$ (assuming a distance of 6 kpc to V838 Mon; Sparks 2006; Afsar & Bond 2006). These mass estimates can be reconciled with the mass estimate from the visible and IR observations if most, $\gtrsim 90\%$, of the CO molecules have been photo-dissociated by the emission of the surrounding B-stars, which were reported to exist there (Afsar & Bond 2006). Many systems are known where stellar radiation destroys CO molecules while the warm dust survives, e.g., around A-stars (Greaves et al. 2000).

The conclusion from the $\sim 10^2 - 10^3 M_{\odot}$ estimated mass in the echoing region is that the echoing material is of ISM origin, as suggested in Tyllenda (2004) and Tyllenda, Soker & Szczerba (2005), rather than it resulted from previous eruptions as claimed by, e.g., Bond and collaborators (Bond et al. 2003; Bond 2006). Even if clear symmetries are seen in the echo images, they simply reflect the echo geometry. Also, the progenitor stellar wind could have shaped part of the echoing gas prior to eruption. More than that, it is quite likely that the echoing material reveals an axial-symmetric structure, resulting from the relative motion of the progenitor of V838 Mon through the ISM, e.g., a bow shock, as discussed in Tyllenda (2004) and Tyllenda et al. (2005).

2.2. The Mass in the Inflated Envelope and Wind

Many talks during the meeting were devoted to the observation of V838 Mon itself and to its luminosity and temperature evolution (e.g., reviews by Henden 2006; Munari 2006). However, the lack of any new attempt to derive physical parameters relevant to models of V838 Mon was quite disappointing. In particular, no new mass estimate was given to the inflated envelope and ejected mass, so we are left with the values given by Tyllenda (2005). The mass lost from the system that was found by Tyllenda (2005), translated to the new distance estimate of 6 kpc, is $M_{\text{lost}} \simeq 0.0025M_{\odot}$ if a Planck mean opacity is used, and $M_{\text{lost}} \simeq 0.3M_{\odot}$ if a Rosseland mean opacity is used. As well known, the opacity should be closer to the Rosseland mean opacity (at the meeting this was discussed by Pavlenko 2006). V838 Mon has strong water absorption lines (Lynch et al. 2006), which indicate that a mass of $M_{\text{lost}} \sim 0.04M_{\odot}$ was lost by V838 Mon during the eruption (Lynch et al. 2004; L. Bernstein private communication 2006). The conclusion from the above is that the mass lost by V838 Mon is $M_{\text{lost}} \simeq 0.04 - 0.2M_{\odot}$. We hope more attempts will be made to derive this mass, with the caution that the envelope might be aspherical (Lane et al. 2005).

The mass of the inflated envelope, i.e. gravitationally contracting in the decline, is $M_{\text{env}} \simeq 0.11M_{\odot}$ for a distance of $D = 6\text{ kpc}$ (it was scaled from a mass of $0.22M_{\odot}$ derived by Tyllenda [2005] for the then assumed distance of

$D = 8$ kpc). Over all, the inflated envelope and the expelled mass are added to a total of extended (i.e. strongly affected) mass of $M_{\text{extended}} \simeq 0.1 - 0.3 M_{\odot}$.

This extended mass completely rules out any model where a collision of planets with a star caused the V838 Mon eruption. In principle, a collision of a main sequence star with a planet can lead to a transient event, but not as bright as that of V838 Mon. Retter (Retter et al. 2006b) presented the planet capture model of V838 Mon (Retter & Marom 2003; Retter et al. 2006a). The paper by Retter et al. (2006a) suffers from severe problems: (1) They define a ‘stopping radius’. This is an ill-defined term. A planet inside a stellar envelope will not stop at any radius. It will continue to spiral-in until being evaporated or torn apart by tidal forces, or will overflow its Roche lobe. They write: “. . . the impacting planet has come to rest relative to the stellar envelope, i.e. when it has transferred all (or most of) its kinetic energy to the parent star.” But the kinetic energy of the planets only increases as it spirals-in in a Keplerian orbit. If the planets really stops, then it will sink inward. (2) To account for the large energy emitted by V838 Mon they need one or more of the planets to penetrate deep into the stellar envelope. However, a large amount of energy liberated deep in an envelope goes mainly to lift the outer envelope gas. When the planet is deep inside the star the outer envelope mass is much larger than the planet mass, and the envelope will expand by a very small factor, and with not much increase in luminosity. (3) They consider either a model with three planets or one. The model with three planets suffers from that no three stable orbits can be given for the time prior to eruption. The model with one planet requires the planets to get deep into the envelope, where most energy will go to slightly lift the outer stellar envelope layers (point 2 above). (4) From obvious energetic reasons it is impossible to eject more mass than was accreted. Numerical simulations give that mass lost in a merger is of a few percent of the accreted star. V838 Mon lost a mass of $M_{\text{lost}} \gtrsim 0.04 M_{\odot}$, and no planet, nor even a brown dwarf, can account for this.

3. Other Types of Eruptive Objects That Do Not Fit V838 Mon

In a previous paper we (Tylenda & Soker 2006, see the table in that paper) compared the stellar merger model with models based on thermonuclear runaway eruptions. It was found that neither models based on born-again AGB stars nor models based on novae can account for the properties of V838 Mon. In particular, born-again AGB stars and novae (or nova-like systems) fade as very hot (blue) objects. This is contrary to the behavior of V838 Mon in the last 4.5 years. This was the consensus in the meeting. Some people even asked specifically that we stop calling V838 Mon a nova-like event.

Hirschi (2006) showed that evolution of single massive stars cannot lead to any event similar to that of V838 Mon.

Lawlor (2006) admitted that his previously suggested model, based on born again AGB star which accretes mass from a companion, cannot account for the late behavior of V838 Mon (see also Tylenda & Soker 2006).

Adding to these the failure of the planet model to account for the energy and envelope mass of V838 Mon, we are left with the stellar merger model as the only model which can account for all the observations presented at the meeting.

4. The Stellar Merger Model

4.1. Merger Events: General Considerations

The discovery of the eruption of V838 Mon in 2002 and subsequent analysis of its observed evolution, as well as of other similar objects (V4332 Sgr, M31 RV), have lead us to suggest that these observed events were likely to be due to stellar mergers (Soker & Tylenda 2003; Tylenda & Soker 2006). Likewise, an analysis done in Bally & Zinnecker (2005) shows that stellar mergers in cores of young clusters can be source of luminous and spectacular observational events.

Different processes can lead to stellar mergers. In dense stellar systems direct collisions of two stars can quite easily happen leading in most cases to a merger. In multiple star systems dynamical interactions between the components or encounters between the system and other stars can destabilize stellar trajectories so that two components collide and merge, and a third star is ejected.

A binary stellar system can lose angular momentum during its evolution, e.g. due to mass loss, so the separation of the components decreases, which may finally lead to a merger. In the latter case, the merger is probably often relatively gentle and does not lead to spectacular events. This happens when the system reaches and keeps synchronization until the very merger. The relative velocity between the matter elements from different components is then very low, there is no violent shock heating and the orbital energy is released on a very long time scale. However when the binary component mass ratio is low (but not too low for a bright event) the secondary is unable to maintain the primary in synchronized rotation, so the so-called Darwin instability sets in and the merger takes place with a large difference between the orbital velocity of the secondary star and the rotational velocity of the primary envelope. In this case the merger is expected to be violent, at least in the initial phase when the large velocity differences are dissipated in shocks. Soker & Tylenda (2007) analyze this case.

The gravitational and kinetic energy of the merging binary system can result in the following observational events:

1. Flash of light. This flash is formed by emission from a strongly shocked gas, in the primary and/or secondary envelope, and will be observed as a flash lasting as long as the secondary is violently slowed-down in the outer regions of the primary star. This can be from few times the dynamical time of the system up to a very long time, depending on the condition of the merging system. For the flash to be bright, the duration should be short, which implies a large relative velocity between the secondary and rotating primary envelope.
2. Gravitational and kinetic energy of matter expelled to large distances, and even leaving the system. The matter that does not leave the system, falls back on a dynamical time scale at its maximum distance, and when it becomes optically thick it contracts on its Kelvin-Helmholtz time scale. The Kelvin-Helmholtz time scale of the inflated envelope is much shorter than the Kelvin-Helmholtz time scale of the primary, due to the very high luminosity and very low mass of the inflated envelope. The large energy in the inflated envelope and its relatively short contraction time implies that

the energy deposited in the inflated envelope results in a bright phase of the merging system, lasting much longer than the initial flash (for detail of this process as applied to V383 Mon, see Tylenda 2005, and Tylenda & Soker 2006).

3. Gravitational energy of the expanding inner layers of the primary and/or secondary (even destroying the secondary). The mass of the layer above the location of the secondary star will be large when the secondary penetrates the deep layers of the primary star. When the inner layers of the primary finally relax to equilibrium it will be on a very long Kelvin-Helmholtz time scale.

Only the first two energy channels are relevant for the formation of bright transient event from merger. We term these type of events *mergebusts*. The last process will not form any bright event. Therefore, any model where planets penetrate deep into the primary star, although liberating huge amount of orbital gravitational energy, cannot account for the eruption of V838 Mon, or of any other bright event.

4.2. The Merger Model of V838 Mon

To account for the eruption of V838 Mon we suggest that the merging stars had the following properties (see Tylenda & Soker 2006 for detail):

1. The system was young. This is supported by the B-type primary star (Tylenda et al. 2005), the claim for a young stellar population in its vicinity (Afsar & Bond 2006), and the fact that the echoing matter is most likely of interstellar origin (as discussed in Sect. 2.1).
2. The primary was a $\sim 8M_{\odot}$ main sequence star, as deduced from observations in Tylenda et al. (2005).
3. We assume that the secondary star was of mass $M_2 \simeq 0.3M_{\odot}$, which was formed with the primary star. This low mass implies that the secondary star was a pre-main sequence star at the time of the merger.
4. We assume that the orbit prior to merger was of very high eccentricity, or the secondary was deflected toward the primary by multi-stellar interactions.
5. From simple energetic considerations we have found that in order to inflate a huge envelope, as observed in V838 Mon, the eccentricity should be high, $e \gtrsim 0.9$, and the low mass companion should be indeed a pre-main sequence star, such that less energy is required to disrupt it.
6. This has been confirmed by running a ready to use numerical code (MMAS, version 1.6, package described in Lombardi et al. 2002, 2003). These simulations show that the inflated envelope comes almost entirely from the secondary star.
7. Based on full 3D numerical simulations (e.g., Freitag & Benz 2005; Dale & Davies 2006) we know that merging binary systems with high eccentricity

(or approaching from infinity, which is equal to taking $e = 1$), result in 2-4 episodes of energy dissipation and mass loss ejection. This is exactly what is inferred for V838 Mon (see a detailed analysis in Tylenda 2005): one moderate expansion, followed in a month by ejection of two massive shells separated in time by a few days. The episodes of mass loss ejection follow the semi periodic variation in orbital separation. Such an in-and-out separation of the two merging stars is generic to merger processes. Even a neutron star starting with a circular orbit around an evolved star has semi-oscillatory separation variations as it merges with the evolved star (Terman, Taam, & Hernquist 1995).

8. It is quite possible that the binary system became interacting before the final merger which caused the 2002 eruption. This may explain the possible variability of the V838 Mon progenitor a few years before the outburst (Kimeswenger 2006).

It should be emphasize again that the only theoretical model that existed before the eruption of V838 Mon, and which could have in principle predicted the properties of V838 Mon, is the stellar merger model. All other models (novae; born again AGB stars; models based on planets) had to *invent* specific properties to account for V838 Mon, and even then failed to explain basic properties of V838 Mon. The talks and discussions in the meeting at La Palma strengthened this point.

4.3. Open questions

The main drawback of our merger model is that it is based on estimates and approximate considerations. The simple simulations presented by Tylenda & Soker (2006; their Sect. 4.2) only demonstrate that an inflated envelope can be formed from a merger. Realistic simulations should provide a three-dimensional structure of the inflated envelope, its evolution after merger, and the expected light curve. This would however be a very complex task involving three-dimensional radiation-hydrodynamics. What is more secure as far as physics goes, is that main sequence stars accreting at a high rate can swell to hundreds of solar radii. In addition to previous papers showing this swelling (cited by Soker & Tylenda 2003), in his talk Lawlor (2006) presented similar results when he compared the merger model with the born-again model. We hope that people who study main-sequence stellar mergers will be invited to the next meeting on V838 Mon and related objects.

Another open question concerns the statistics. There was no consensus at the meeting as to which objects should be grouped with V838 Mon (Kimeswenger 2006). Therefore, the occurrence rate of such events in the galaxy (and beyond) is unknown. The progenitor of M31-RV was a low mass star (Siegel & Bond 2006), adding to the potential population that can form such event. From the theoretical side, if we consider all types of *mergebusts*, i.e., violent mergers (Soker & Tylenda 2007), of both massive and low mass stars, a crude estimate leads to a galactic event rate of once every 10-50 years.

4.4. Predictions

The violent merger model for bright transient events, we suggest to call them *mergebursts*, has some predictions for future observations.

(1) As a result of the gravitational contraction of the inflated envelope V838 Mon will decline in luminosity with a slowly rising effective temperature. The time scale of the event will increase with time and the decline will last many decades (perhaps even centuries). No excursion to very high effective temperatures ($\gtrsim 10^5$ K) will occur.

(2) The inflated envelope has a relatively large specific angular momentum. As the envelope shrinks, the rotation velocity increases, and when it shrinks to a radius of $R \lesssim 100R_\odot$, it will be possible to detect this rotation velocity $v_{\text{rot}} \simeq (10 - 40)(R/100R_\odot)^{-1} \text{ km s}^{-1}$.

(3) A dense dusty disk, resulting from the merger event, might be revealed as the star shrinks.

(4) Convective motions in the differentially rotating envelope can amplify magnetic fields. Mass loss would then be an efficient process of angular momentum loss from the envelope. This would weaken the effects discussed in the above two points.

(5) The echo structure will deviate more from a spherical morphology, resembling more an ISM cloud. Signs of a bow-shock+tail structure produced by a star blowing wind and moving through the ISM might be present.

(6) No close, $a \lesssim 1$ AU, companion will be detected around V838 Mon. Companions at larger orbital separations are possible. Such a companion might have been the perturbing body that cause the merger event.

(7) The merger event could have been caused by a third lower mass star, $M_3 \lesssim M_2 \simeq 0.3M_\odot$, that was ejected from the system. Such a star might be found escaping from V838 Mon with a speed of $\sim 10 - 100 \text{ km s}^{-1}$.

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